7. IR standards and Absolute Calibration

7.1 Ground-based Photometry

The words of Bouchet et al. (1991, p. 409) should be kept in mind when practicing IR photometry:

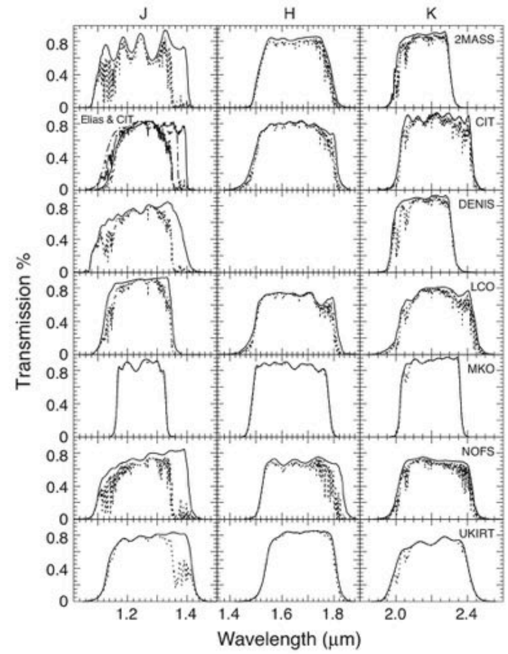
“It is usually believed that there are as many JHKLM photometric systems as observatories. Although all of them are derived from the JHKL system of Glass (1974), which followed the pioneering work by Johnson (the ‘Arizona’ system defined by Johnson (1965) and Johnson et al. (1966)), and use the ‘same’ InSb detectors, the filters used can be significantly different, and the passbands are affected by the atmospheric transparency which varies from one site to the other. The detectors can also be different.”

Detailed comparison of one photometric system to another requires careful attention to details of the photometric zero points (what defines 0 mag in the system), filter profiles, adopted filter wavelength definition, color transformations, and adopted absolute calibration for 0 mag.

Notes:
References: Bouchet, P. et al. (1991). "JHKLM standard stars in the ESO system." Astronomy and Astrophysics Supplement Series **91**: 409-424.
Glass, I. S. (1974). "JHKL Photometry of 145 Southern Stars [errata: 1974MNSSA..33...71G]." Monthly Notes of the Astronomical Society of South Africa **33**: 53.
Johnson, H. L. (1965). "The absolute calibration of the Arizona photometry." Communications of the Lunar and Planetary Laboratory **3**: 73.
Johnson, H. L., B. Iriarte, R. I. Mitchell and W. Z. Wisniewskj (1966). "UBVRIJKL photometry of the bright stars." Communications of the Lunar and Planetary Laboratory **4**: 99.
See also Johnson --- ARAA
Moro, D. & U. Munari (2000). "The Asiago Database on Photometric Systems (ADPS). I. Census parameters for 167 photometric systems." Astronomy and Astrophysics Supplement Series **147**: 361-628. In 2004, there were 226 systems listed on their website, http://ulisse.pd.astro.it/Astro/ADPS/ .

There is no standard infrared photometric system in use, although in recent years the Mauna Kea set of filters have gained acceptance (Simons & Tokunaga 2002, Tokunaga & Simons 2002, and Tokunaga & Vacca 2005.

The figure to the right shows the filter profiles for various observatories Stephens and Leggett (2004). Note that many of the filters were broader than the atmospheric window. This causes the filter bandwidth to be dependent on the atmospheric transmission. The MKO filters avoid this problem (Simons & Tokunaga (2002).



Notes: References:

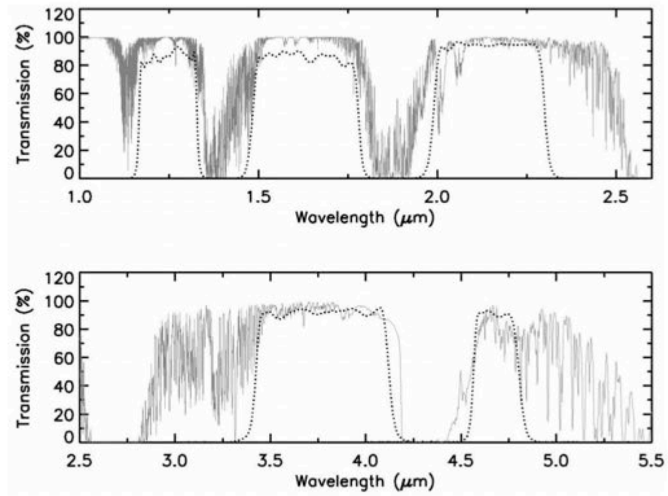
Simons, D. A. & A. Tokunaga (2002). "The Mauna Kea Observatories Near-Infrared Filter Set. I. Defining Optimal 1-5 Micron Bandpasses." Publications of the Astronomical Society of the Pacific **114**: 169-179.

Stephens, D. C. & S. K. Leggett (2004). "JHK Magnitudes for L and T Dwarfs and Infrared Photometric Systems." Publications of the Astronomical Society of the Pacific **116**: 9-21.

Tokunaga, A. T. et al. (2002). "The Mauna Kea Observatories Near-Infrared Filter Set. II. Specifications for a New JHKL'M' Filter Set for Infrared Astronomy." Publications of the Astronomical Society of the Pacific **114**: 180-186.

Tokunaga, A. T. & W. D. Vacca (2005). "The Mauna Kea Observatories Near-Infrared Filter Set. III. Isophotal Wavelengths and Absolute Calibration." Publications of the Astronomical Society of the Pacific **117**: 421-426.

This figure shows the comparison of the MKO filter profiles compared to the atmospheric transmission with 1.0 mm of precipitable water (Tokunaga et al. 2002).

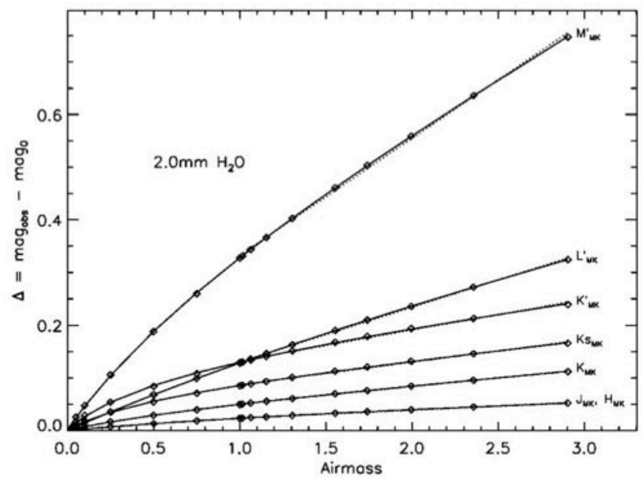


Notes:
Tokunaga, A. T. et al. (2002). "The Mauna Kea Observatories Near-Infrared Filter Set. II. Specifications for a New JHKL'M' Filter Set for Infrared Astronomy."
Publications of the Astronomical Society of the Pacific **114**: 180-186.

Figure showing the atmospheric extinction as a function of airmass for the MKO filters (Tokunaga et al. 2002).

The extinction curves is very close to linear (shown by the dashed line) for airmass of 1.0 or greater.

Note that extrapolation to above the atmosphere (0.0 airmass) is not possible due to the nonlinearity of the atmospheric absorption. The nonlinearity arises from the saturated absorption lines.



Notes:
Tokunaga, A. T. et al. (2002). "The Mauna Kea Observatories Near-Infrared Filter Set. II. Specifications for a New JHKL'M' Filter Set for Infrared Astronomy."
Publications of the Astronomical Society of the Pacific **114**: 180-186.

Note that the wide filters that are affected by the atmospheric transmission have the following problems:

- The filter bandwidth is dependent on the atmospheric conditions, and this affects the effective wavelength.
- The extinction coefficient will be non-linear (Manduca and Bell 1979; Young et al. 1994)
- The color transformation from one system to another will be compromised (Young et al. 1994).

The MKO filter set was designed to minimize the impact of atmospheric absorption while keeping the throughput as high as possible for observing sites greater than 2 km in altitude (Simons and Tokunaga 2002).

Milone and Young (2005) suggest using narrower filters that permit good color transformation between observatories at all altitudes. These narrow filters allow almost linear extrapolation to zero airmass, whereas the MKO filters have a non-linear extrapolation to zero airmass (Tokunaga et al. 2002). However the MKO filters are acceptable for relative photometry in which the signal from a target star is compared to a standard star.

Notes: References:

Manduca, A. and R. A. Bell (1979). "Atmospheric extinction in the near infrared." Publications of the Astronomical Society of the Pacific **91**: 848-854.
Young, A. T., E. F. Milone and C. R. Stagg (1994). "On improving IR photometric passbands." Astronomy and Astrophysics Supplement Series **105**: 259-279.
Milone, E. F. and A. T. Young (2005). "An Improved Infrared Passband System for Ground-based Photometry: Realization." Publications of the Astronomical Society of the Pacific **117**: 485-502.
Tokunaga, A. T., D. A. Simons and W. D. Vacca (2002). "The Mauna Kea Observatories Near-Infrared Filter Set. II. Specifications for a New JHKL'M' Filter Set for Infrared Astronomy." Publications of the Astronomical Society of the Pacific **114**: 180-186.

Selected photometric systems

Name	Bands	References	Notes
Johnson (Arizona)	*JHKLM NQ*	1,2,3,4,5	Earliest near-IR system established
CIT/CTIO (Elias)	*JHK*	6,7	Northern and southern hemispheres
Persson (LCO)	$JHKK_S$	8	Set of faint standards based on CIT/CTIO
ESO	$JHKL'MNQ$	9,10,11	
UKIRT (MKO)	$JHKL'M'$	12,13,14	UKIRT and MKO standards
SAAO (Carter)	*JHKL*	15,16	
Bessell and Brett	*JHKL*	17	Stellar colors on Johnson-Glass system
Tenerife (Kidger)	*JHK*	18,19	Supports Cohen et al. (1999)
2MASS	$JHKK_S$	20,21	Based on Persson standards
UKIDSS	*ZYJHK*	22,23	Based on 2MASS point source catalog

Notes: Only key references are given here. It is necessary to check these references for how the system was developed, the list of standard stars, and color transformation between the various systems

Notes: This is Table 3.8 in Tokunaga, A. T., et al. (2013). Infrared Astronomy Fundamentals. Planets, Stars and Stellar Systems. Volume 2: Astronomical Techniques, Software and Data. T. D. Oswalt & H. E. Bond, p. 99.

References: (1) Johnson (1965) (2) Johnson et al. (1966) (3) Campins et al. (1985) (4) Rieke et al. (1985) (5) Rieke et al. (2008) (6) Elias et al. (1982) (7) Elias et al. (1983) (8) Persson et al. (1998) (9) Bouchet et al. (1991) (10) Bersanelli et al. (1991) (11) van der Bliek et al. (1996) (12) Hawarden et al. (2001) (13) Leggett et al. (2003) (14) Leggett et al. (2006) (15) Carter (1990) (16) Carter and Meadows (2001) (17) Bessell and Brett (1988) (18) Kidger and Mart.n-Luis (2003) (19) Cohen et al. (1999) (20) Skrutskie et al. (2006) (21) Cohen et al. (2003b) (22) Hewett et al. (2006) (23) Hodgkin et al. (2009). Other standard star list: Hunt et al. (1998)

Standards used at Mauna Kea. All of the observatories use the "Mauna Kea filters" for the near-IR (1-5 μm) defined by Simons & Tokunaga (2002) and Tokunaga et al. (2002). These filters are used in most major observatories, such as ESO.

In the mid-IR (8-25 μm), the filters are not standardized and so careful attention to the effective wavelengths is needed. A good resource for mid-IR filters and standards is given by the Gemini Observatory:

https://www.gemini.edu/sciops/instruments/midir-resources

Mid-IR capability at ground-based observatories is very limited. Only Subaru, IRTF, and ESO have mid-IR instruments. The Tokyo Atacama Observatory (TAO) will have mid-IR instruments and this will be one of it's main strengths since the Atacama site has the best atmospheric conditions for the infrared.

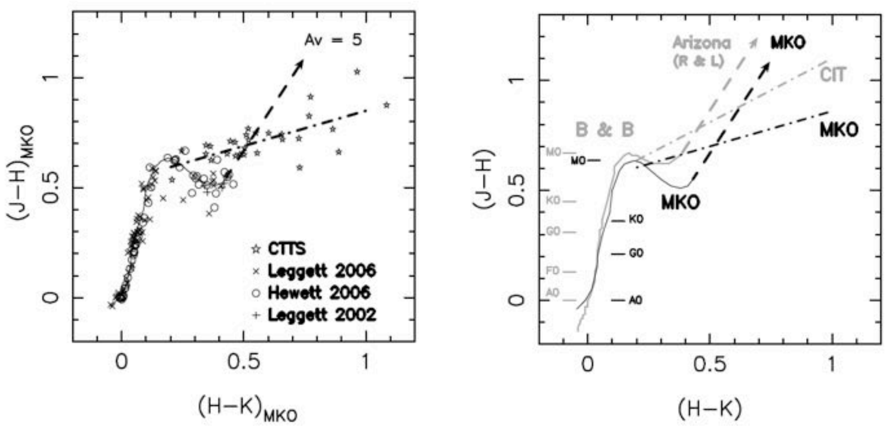
Notes: References:

Simons, D. A. and A. Tokunaga (2002). "The Mauna Kea Observatories Near-Infrared Filter Set. I. Defining Optimal 1-5 Micron Bandpasses." Publications of the Astronomical Society of the Pacific **114**: 169-179.

Tokunaga, A. T., D. A. Simons and W. D. Vacca (2002). "The Mauna Kea Observatories Near-Infrared Filter Set. II. Specifications for a New JHKL'M' Filter Set for Infrared Astronomy." Publications of the Astronomical Society of the Pacific **114**: 180-186.

Status of COMICS from Tae-Soo Pyo:
COMICS is still available. Subaru doesn't have any active decommissioning plan (just passive decommissioning) for any instruments yet.
Currently SWIMS/MIMIZUKU instruments are in Hilo, they are preparing for engineering observations from the next semester.
SWIMS team is considering to open science observations to Subaru users but it is necessary another review process and TBD.
MIMIZUKU team is thinking just engineering observations, so it will not be open to Subaru users.

Color transformations. Since the filters and atmospheric transmission can be different for each observatory, color transformations are necessary to compare data taken with different filters. This figure (Yasui, 2009) shows a color-color diagram showing dwarf stars observed with the MKO filters (left). The comparison to the Arizona and CalTech filter systems are shown on the right. The reddening vector (arrow) and the classical T Tauri star tracks (CTTS; dot-dash lines) are also shown. To compare data sets, it is necessary to transform the colors to a single system.



Notes:

Yasui, C. 2009, Ph.D. Thesis, “The Lifetime of Protostellar Disks in Low-metallicity Environments”.

Here are some references for transforming colors from one system to another:

Leggett et al. (2006) gives color transformations between the MKO photometric system and the UKIRT, LCO, and Two Micron All-Sky Survey (2MASS) systems.

Carpenter (2001) gives the color transformations between the 2MASS and 2MASS and AAO, ARNICA, CIT, DENIS, ESO, LCO (Persson standards), MSSSO, SAAO, and UKIRT photometric systems. See also:
http://www.astro.caltech.edu/~jmc/2mass/v3/transformations/

Notes:

Leggett, S. K., et al. (2006). "JHK observations of faint standard stars in the Mauna Kea Observatories near-infrared photometric system." Monthly Notices of the Royal Astronomical Society **373**: 781-792.

Carpenter, J. M. (2001). "Color Transformations for the 2MASS Second Incremental Data Release." Astronomical Journal **121**: 2851-2871.

7.2 Definition of a Filter Wavelength

As shown in the previous sections, the filter profiles vary greatly. In the case of the JHKLM filter set, this can lead to difficulties in comparing observations made with different filter sets. The most used filter sets in ground-based astronomy today are the 2MASS and MKO sets.

When plotting the flux density of an object observed with a filter a single wavelength (the "monochromatic" wavelength) is chosen to represent the flux density of the source with that filter. In most cases this is only an approximation since the object may have strong emission or absorption lines or bands and the filter may be very broad or have an unusual profile.

There are various definitions for the wavelength of a filter as discussed by Tokunaga and Vacca (2005), Rieke et al. (2008), Bessell and Murphy (2012), and Bohlin (2014). In this section we discuss several of the main ones.

Notes: References:

Tokunaga, A. T. and W. D. Vacca (2005). "The Mauna Kea Observatories Near-Infrared Filter Set. III. Isophotal Wavelengths and Absolute Calibration." Publications of the Astronomical Society of the Pacific **117**: 421-426; erratum "Publications of the Astronomical Society of the Pacific **117**: 1459-1459.

Rieke, G. H. et al. (2008). "Absolute Physical Calibration in the Infrared." The Astronomical Journal **135**: 2245-2263.

Bessell, M. and S. Murphy (2012). "Spectrophotometric Libraries, Revised Photonic Passbands, and Zero Points for UBVRI, Hipparcos, and Tycho Photometry." Publications of the Astronomical Society of the Pacific **124**: 140-157.

Bohlin, R. C. et al. (2014). "Techniques and Review of Absolute Flux Calibration from the Ultraviolet to the Mid-Infrared." Publications of the Astronomical Society of the Pacific **126**: 711.

7.2.1 Isophotol wavelength and other wavelength definitions

$F_\lambda(\lambda)$ is the flux density of a source as a function of wavelength. Then the number of photoelectrons detected per second is given by:

$$N_p = \int F_\lambda(\lambda)S(\lambda)/h\nu d\lambda$$
$$= \frac{1}{hc}\int \lambda F_\lambda(\lambda)S(\lambda)d\lambda.$$

$S(\lambda)$ is the total system response given by

$$S(\lambda) = T(\lambda)Q(\lambda)R(\lambda)A_{\mathrm{tel}}$$

where $T(\lambda)$ is the atmospheric transmission; $Q(\lambda)$ is the product of the throughput of the telescope, instrument, and quantum efficiency of the detector; $R(\lambda)$ is the filter response function; and A_{tel} is the telescope collecting area. From the equation for N_p and the mean value theorem for integration, there exists an isophotal wavelength, λ_{iso}, such that

$$F_\lambda(\lambda_{\mathrm{iso}})\int \lambda S(\lambda)d\lambda = \int \lambda F_\lambda(\lambda)S(\lambda)d\lambda.$$

Notes:

Rearranging the equation, we get

$$F_\lambda(\lambda_{\text{iso}}) = \langle F_\lambda \rangle = \frac{\int \lambda F_\lambda(\lambda) S(\lambda) d\lambda}{\int \lambda S(\lambda) d\lambda}.$$

$F_\lambda(\lambda_{iso})$ is therefore the mean value of the intrinsic flux density above the atmosphere over the passband of the filter.

Or you can say λ_{iso} is the wavelength at which the monochromatic flux density, $F_\lambda(\lambda)$, equals the mean flux in the passband.

Notes:

Other definitions of the filter wavelength does not depend on knowing the flux density of the source. For example Rieke et al. (2008) use the mean wavelength defined by

$$\lambda_0 = \frac{\int \lambda S(\lambda) d\lambda}{\int S(\lambda) d\lambda}$$

For the calibration of the Spitzer data, Reach et al. (2005) define the nominal wavelength as

$$\lambda_0 = \frac{\int \lambda \nu^{-1} R \, d\nu}{\int \nu^{-1} R \, d\nu}$$

where R is the system spectral response in units of electrons per photon at frequency ν.

Other definitions, advantages and disadvantages, are given by Tokunaga and Vacca (2005) and Bessell and Murphy (2012) in the appendices to their papers. Bessel and Murphy (2012) adopt the mean wavelength and the pivot wavelength, both are independent of the source flux density.

Notes:

Reach, W. T. et al. (2005). "Absolute Calibration of the Infrared Array Camera on the Spitzer Space Telescope." Publications of the Astronomical Society of the Pacific **117**: 978-990.
Rieke, G. H. et al. (2008). "Absolute Physical Calibration in the Infrared." The Astronomical Journal **135**: 2245-2263.
Tokunaga, A. T. and W. D. Vacca (2005). "The Mauna Kea Observatories Near-Infrared Filter Set. III. Isophotal Wavelengths and Absolute Calibration." Publications of the Astronomical Society of the Pacific **117**: 421-426; erratum "Publications of the Astronomical Society of the Pacific **117**: 1459-1459.
Bessell, M. and S. Murphy (2012). "Spectrophotometric Libraries, Revised Photonic Passbands, and Zero Points for UBVRI, Hipparcos, and Tycho Photometry." Publications of the Astronomical Society of the Pacific **124**: 140-157.

The pivot wavelength is defined as:

$$\lambda_p = \sqrt{\frac{\int \lambda S(\lambda) d\lambda}{\int \lambda^{-1} S(\lambda) d\lambda}}$$

and it allows the conversion of flux density from wavelength units to frequency units:

$$\langle F_\nu \rangle = \langle F_\lambda \rangle \lambda_p^2 / c$$

Notes:

Wavelengths according to different definitions (Tokunaga and Vacca 2005):

Isophotal, Effective, Mean, and Pivot Wavelengths for the MKO-NIR Filters

Filter	λ_{iso} (μm)	λ_{eff} (μm)	λ'_{eff} (μm)	λ_0 (μm)	λ_{pivot} (μm)
J	1.250	1.241	1.243	1.248	1.247
H	1.644	1.615	1.619	1.630	1.628
K'	2.121	2.106	2.111	2.123	2.121
K_s	2.149	2.138	2.141	2.151	2.150
K	2.198	2.186	2.190	2.202	2.200
L'	3.754	3.717	3.727	3.757	3.752
M'	4.702	4.680	4.681	4.684	4.684

Bessel and Murphy (2012) adopt the mean wavelength and the pivot wavelength, both are independent of the source flux density. **All filter systems should provide these two numbers, along with the filter profile.** This would provide consistency into the future.

Notes:

Tokunaga, A. T. and W. D. Vacca (2005). "The Mauna Kea Observatories Near-Infrared Filter Set. III. Isophotal Wavelengths and Absolute Calibration." Publications of the Astronomical Society of the Pacific **117**: 421-426.

Bessell, M. and S. Murphy (2012). "Spectrophotometric Libraries, Revised Photonic Passbands, and Zero Points for UBVRI, Hipparcos, and Tycho Photometry." Publications of the Astronomical Society of the Pacific **124**: 140-157.

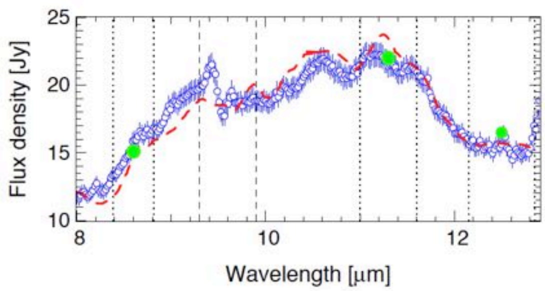


Fig. 3. Low-resolution spectrum of HD179218 (open circles with error bars) scaled to the measured photometry at 11.3 μm (green filled circles). The red dashed line is the corresponding Spitzer/IRS spectrum. The vertical dotted lines denote the bandwidth of the PAH-1, PAH-2, and Si-6 filters. The vertical dashed line indicates the region of the atmospheric ozone feature where proper spectroscopic calibration is cumbersome.

Taha et al. (2017), fig. 3, showing comparison of spectra with photometric bandpass.

This shows the filter width superimposed on the spectrum. The spectrum is not smooth, so the isophotal wavelength is difficult to calculate and changes from source to source. Hence the use of the pivot wavelength is better.

Notes:

Taha, A. S. et al. (2017) "The spatial extent of Polycyclic Aromatic Hydrocarbons emission in the Herbig star HD 179218." ArXiv e-prints 1711.05202.

7.2.2 Correction to a Monochromatic Wavelength

As mentioned previously, filter bandpass are often very broad. Therefore if we represent the flux density of a source at a single filter wavelength (a "monochromatic" wavelength) a good approximation would be to plot the flux density at the isophotol wavelength.

If you now want to plot the flux density of a hot star and a cool star at the same isophotal wavelength then a color correction is needed to take into account the different SEDs of the stars. The color correction can be given as a factor K in the equation:

$$F_\lambda^{\text{obj}}(\lambda_{\text{iso}}^{\text{std}}) = K\langle F_\lambda^{\text{obj}}\rangle$$

$\langle F_\lambda^{\text{obj}}\rangle$ is the mean flux density for the object as defined on slide 7-12. The color correction factor K adjusts the flux density to the isophotol wavelength of the standard. K can be calculated for a range of SEDs, such as blackbodies or power laws.

Notes:

7.2.3 Example of Spitzer observations

A source-independent definition for the wavelength is used and then a correction is applied to to correct for the SED of the object being observed. To accomplish this, the Spitzer archive gives a quoted flux density F_ν^{quote} at a nominal wavelength λ_0 ($= c/\nu_0$) for a flat-spectrum source F_ν^{nom} where $\nu F_\nu^{nom} = constant$. A correction factor is applied to take into account the actual SED of the source. This convention is used the IRAS, ISO, COBE, and WISE missions and it allows the use of a monochromatic wavelength without inconsistency for a wide range of source SEDs. For more details, see the IRAC Instrument Handbook, section 4.4.

The data is calibrated and corrected as follows. The number of electrons per unit of time from a source with spectrum F_ν is

$$N_e = A \int (F_\nu / h\nu) \; R d\nu$$

where A is the telescope area and R is the system spectral response in units of electrons per photon. R includes all of the transmission and reflection factors of the optics, transmission of the filters, the detector quantum efficiency, and the diffraction and scattered light losses.

Notes: Spitzer IRAC color correction: http://irsa.ipac.caltech.edu/data/SPITZER/docs/irac/iracinstrumenthandbook/18/

The calibration factor is the ratio of the flux density at the nominal wavelength λ_0 to the observed electrons per sec:

$$C = \frac{F^*_{\nu 0}}{N_e} K^*$$

where the color correction is

$$K = \frac{\int (F_\nu / F_{\nu 0})(\nu/\nu o)^{-1}\, R\, d\nu}{\int (\nu/\nu o)^{-2}\, R\, d\nu}$$

The nominal wavelength is defined so that the correction factor K is a minimum. It is:

$$\lambda_0 = \frac{\int \lambda\, (\nu/\nu o)^{-1} R\, d\nu}{\int (\nu/\nu o)^{-1}\, R\, d\nu} = \mathrm{c}\frac{\int \nu^{-2}\, R\, d\nu}{\int \nu^{-1}\, R\, d\nu}$$

Notes:

Therefore plotting data using the nominal wavelength removes most of the SED dependence. For better accuracy one can take the quoted flux density from the archive and apply the color correction as follows:

$$F_{\nu o} = \frac{F_{\nu o}^{quot}}{K}$$

See http://irsa.ipac.caltech.edu/data/SPITZER/docs/irac/iracinstrumenthandbook/18/ for the details and the color correction term K.

Notes:

7.3 Absolute Calibration.

The calibration of a measurement to a flux density above the atmosphere involves direct and indirect methods of comparing observations to primary calibration stars with a known flux density. Historically the star Vega (HR 7001; alpha Lyr) has been an important primary flux calibration star due to the fact that its flux density was measured directly at 0.55 μm with respect to a calibrated black body source (Hayes 1985). This section provides a *very* brief summary of the current state of the absolute calibration in the infrared.

The absolute calibration of Vega and extension to the IR has discussed in detail by Cohen et al. (1992) and Mégessier (1995). Tokunaga and Vacca (2005) find that the near-IR flux densities for Vega given by these authors are nearly identical, with uncertainties of 1.5-2.0%. Since Vega was found to have an IR excess and is suspected to be a variable star, Cohen et al. (1992) recommended the use of Sirius (HR 2491) as a primary standard.

Cohen et al. (1992) chose zero magnitude for Vega in the IR. The absolute flux density was tied to Vega at 0.55 μm and extrapolated to the IR using a stellar model. Note that in other magnitude systems Vega has a magnitude of 0.03 at 0.55 μm (for example, Bessell & Murphy 2012).

Notes: Hayes, D. S. (1985). Stellar absolute fluxes and energy distributions from 0.32 to 4.0 microns. Calibration of Fundamental Stellar Quantities, IAU Symp. 111. editors D. S. Hayes, L. E. Pasinetti & A. G. D. Philip, D. Reidel Pub. Co., 225-249.
Cohen, M. et al. (1992). "Spectral irradiance calibration in the infrared. I - Ground-based and IRAS broadband calibrations." Astronomical Journal **104**: 1650-1657.
Mégessier, C. (1995). "Accuracy of the astrophysical absolute flux calibrations: visible and near-infrared." Astronomy and Astrophysics **296**: 771.
Bessell, M. and S. Murphy (2012). "Spectrophotometric Libraries, Revised Photonic Passbands, and Zero Points for UBVRI, Hipparcos, and Tycho Photometry." Publications of the Astronomical Society of the Pacific **124**: 140-157.

Isophotal Wavelength, Isophotol Frequency, and Flux Density for Vega

Filter	λ_{iso} (μm)	F_λ (W m^{-2} μm^{-1})	ν_{iso} (x10^{14} Hz)	F_ν(Jy)
V	0.5446	3.68E-08	5.490	3630
J	1.250	3.01E-09	2.394	1560
H	1.644	1.18E-09	1.802	1050
K′	2.121	4.57E-10	1.413	686
K_s	2.149	4.35E-10	1.395	670
K	2.198	4.00E-10	1.364	645
L′	3.754	5.31E-11	0.7982	249
M′	4.702	2.22E-11	0.6350	163

This table is based on Tokunaga & Vacca (2005a,b). The flux densities are based on the absolute calibration determined by Cohen et al. (1992).

Note that $\lambda_{iso} \neq c/\nu_{iso}$.

Notes:

Tokunaga, A. T. and W. D. Vacca (2005a). "The Mauna Kea Observatories Near-Infrared Filter Set. III. Isophotal Wavelengths and Absolute Calibration." Publications of the Astronomical Society of the Pacific **117**: 421-426.
Tokunaga, A. T. and W. D. Vacca (2005b). "``The Mauna Kea Observatories Near-Infrared Filter Set. III. Isophotal Wavelengths and Absolute Calibration'' (erratum)." Publications of the Astronomical Society of the Pacific **117**: 1459-1459.
Cohen, M., R. G. Walker and F. C. Witteborn (1992). "Spectral irradiance calibration in the infrared. II - Alpha Tau and the recalibration of the IRAS low resolution spectrometer." Astronomical Journal **104**: 2030-2044.

In a series of paper, Cohen and his collaborators have developed a network of near-IR and mid-IR standards based on a common system during the years 1992-2003, and it covered the 2MASS, IRAS, Spitzer, WISE, AKARI data sets.

Price (2004) and Price et al. (2004) give a summary of the results of these papers and their connection to the MSX absolute calibration work.

Engelke et al. (2010) has proposed using 109 Vir (HR 5511) and Sirius (HR 2491) as primary standards. They propose an absolute calibration for 0.0 mag spanning the uv to 30 μm. This work is consistent with Cohen et al. (1992) and Rieke et al. (2008) to about 2%.

For wavelengths longer that 30 μm, the absolute calibration determined by Herschel can be used. This is discussed by Bendo et al. (2013) and Balog et al. (2014).

Notes: For more details on the absolute calibration work up to 2011, see Tokunaga, A. T., W. D. Vacca and E. T. Young (2013). Infrared Astronomy Fundamentals. Planets, Stars and Stellar Systems. T. D. Oswalt and H. E. Bond. Dordrecht, Springer Science+Business Media. vol. 2, Astronomical Techniques, Software, and Data**:** 99-174.

Engelke, C. W. et al. (2010). "Spectral Irradiance Calibration in the Infrared. XVII. Zero-magnitude Broadband Flux Reference for Visible-to-infrared Photometry." The Astronomical Journal **140**: 1919-1928.
Balog, Z., T. et al. (2014). "The Herschel-PACS photometer calibration. Point-source flux calibration for scan maps." Experimental Astronomy **37**: 129-160.
Bendo, G. J. et al. (2013). "Flux calibration of the Herschel SPIRE photometer." Monthly Notices of the Royal Astronomical Society 433: 3062-3078.

7.3 AB magnitudes

The AB (absolute) magnitude was defined by Oke and Gunn (1983) as

$$m_{AB} = -2.5 \log f_v - 48.60$$

where f_v has units ergs s^{-1} cm^{-2} Hz^{-1} and the constant is chosen to that the AB magnitude of Vega at 5480 nm is +0.03. By this definition, Vega has a flux density of 3.53×10^{-20} ergs s^{-1} cm^{-2} Hz^{-1} .

The great benefit of this magnitude definition is that one can easily go from magnitude to flux density units.

If f_v is expressed in Jy units, then

$$m_{AB} = -2.5 \log\left(\frac{f_v}{Jy}\right) + 8.90 = -2.5 \log\left(\frac{f_v}{3631\ Jy}\right)$$

Discussion of the AB magnitude can be found in Bessell and Murphy (2012), Fukugita et al. (1996), and Tonry et al. (2012) among many others.

Notes:

Oke, J. B. and J. E. Gunn (1983). "Secondary standard stars for absolute spectrophotometry." Astrophysical Journal **266**: 713-717.
Fukugita, M., T. Et al. (1996). "The Sloan Digital Sky Survey Photometric System." Astronomical Journal **111**: 1748.
Tonry, J. L. et al. (2012). "The Pan-STARRS1 Photometric System." The Astrophysical Journal **750**.

Note that the AB magnitude discussion by Tokunaga and Vacca (2005) is not consistent with current practice and should be avoided.

Flux densities are also published in Angstrom units (ergs s^{-1} cm^{-2} $Å^{-1}$). The conversion to frequency units can be derived starting with the relations

$$\nu f_{\nu} = \lambda f_{\nu}; \quad f_{\nu} = \frac{\lambda^2}{c} f_{\lambda}$$

Then

$$\frac{f_{\nu}}{Jy} = 3.33\text{x}104 \left(\frac{\lambda}{Å}\right) \frac{f_{\lambda}}{ergs\, s^{-1}\, cm^{-2}\, Å^{-1}}$$

Notes: